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DIASTROPHISM AND THE FORMATIVE PROCESSES. IV
REJUVENATION OF THE CONTINENTS

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That extensive peneplanation and wide sea-transgression had already taken place as early as the Ordovician period will scarcely be questioned by those who have studied the relations of the Paleozoic to the Proterozoic and Archean terranes. That wide peneplanation and sea-transgression has taken place repeatedly since is equally attested by ample evidence. This is equivalent to saying that peneplanation has been accomplished in periods that are only a fraction of the whole stratigraphic eon. This in turn implies that unless there had been some form of rejuvenation of the continents they would have been submerged early in geological history and the course of subsequent events would have followed lines far different from those that are actually recorded. The relative rapidity of the process of planation, slow as it is, appears the more declared when we recall that the original reliefs in the earliest eras, the Archean and the Proterozoic, were at once more impressive, more complex, and more resistant than those of the later eras. On no continent perhaps was this difference more notable than on North America. And yet, notwithstanding the intricacy and strength of the early reliefs, about one-half of North America was not only well peneplaned as early as the Mid-Ordovician stage, but it was already covered by a wide, shallow sea, and there is indirect evidence that the rest of the continent had been brought to a relatively low level. While as yet studies on the peneplanation of some of the continents are little more than reconnaissances, there is sufficient evidence from such partial observations to warrant the belief that great progress toward a base-level had been made on all continents as early as the Ordovician period.

To broaden the support of these conclusions, it may be noted that the evidence of peneplanation is not confined to beveling surfaces cutting across upturned beds, or even to these combined with the wide extension of epicontinental strata. There is evidence of much cogency, though indirect and inferential, in the relative scantiness of terrigenous silts in the beds laid down near the land. Had the surface near the submerged areas remained high, the terrigenous silts must have had a nature and abundance appropriate to the drainage of high ground and would thus have testified to the fact of elevation. But some of the formations that mark the maximum sea-transgressions show a singular lack of coarse and abundant terrigenous silts. There were limestones that were certainly laid down in shallow, agitated water and yet maintained a high degree of purity, even on close approach to lands that were then emergent. This seems quite clearly to imply a low land surface from which only limited wash was derived. This inference is quite in harmony with the nature of the case, for a peneplanation that was effective enough to reduce a large fraction of the continent to a plain upon which the sea could creep forth would almost inevitably have reduced the remainder to low relief.

There is no need to dwell at length upon the processes of planation further than to recall the conception that runs through this discussion, the central feature of which is the close adjustment of a group of co-ordinate processes to the sea-surface as the controlling agency. The processes above the sea-surface embrace all those that gradually lower the land to the level of the sea at which their efficiency ceases. The processes below the sea-level embrace all those that co-operate with these in staying the terrigenous silts at the sea-border and building them into shelves just beneath the sea-surface. The mature result is a continental terrace, formed of a girdling sea-shelf continuous with the peneplain of the land, the joint product of base-leveling on the reliefs, wave-cutting at the edge of the land, and shelf-building under the edge of the sea. All these were automatically adjusted to one another and to the sea-surface.

The slow partial filling of the sea that ran hand in hand with this gradation lifted the water-level, aided its landward progress and made room for new depositions on the surface of the growing shelf. Given sufficient time without disturbance, the process would inevitably have reduced the whole summit of the continent to a plain and even have submerged it beneath the sea-surface. The ultimate result would have been the reduction of the entire continental surface to a single terrace-top covered by an unbroken shelf-sea.

We have already noted that such a degree of progress toward complete peneplanation and sea-transgression had been made by the Mid-Ordovician stage that complete submergence must inevitably have ensued before the close of Paleozoic history, if there had not intervened some form of continental rejuvenation.

It is clear, however, that the prolonged state of quiescence requisite for complete base-leveling and submergence never was realized. The continuity of the land is attested by the terrigenous deposits that at no time were completely absent. The continuity of land life, after its early introduction, is attested by its own record and by evolutionary evidences. This testimony to the continuity of the land and of the land life would be cogent evidence of the rejuvenation of the continents if it stood alone. But it is reinforced by the record of the deformations that interrupted the course of earth history and that are yet to be sketched but may here be anticipated.

But, if these are facts of history, they can scarcely stand alone. The fact of continental rejuvenation implies suitable conditions and modes of action in the body deformed. If it is really true that the continents have been rejuvenated instead of being replaced by protrusions somewhere else, there is in this an intimation of appropriate conditions in the continents themselves. Either the continental matter was lighter than the suboceanic matter, or the attitude of continents to the basins was such as to favor a renewal of the protrusion of the continents, or else both of these combined their good offices, as is most probable. There do not seem to be other competent alternatives.

If the rejuvenation really occurred at intervals, as implied in the statements already made, while the denudation of the continents, the loading of the borders of the basins, the loss of heat, the internal changes and other assigned agencies of deformation have been continuous, there must apparently have been *some adequate means of accumulating the constantly growing stresses* until a stress-limit was reached and yielding followed. This power of accumulation must have been *adequate* to the deformative results that followed. This forces a consideration of internal conditions.

The critical question that now arises is this:

Is the earth essentially a plastic body or at most a visco-solid, as so long held, or is it essentially an elastico-rigid body? This seems to me nearly equivalent to the question: Is the earth essentially a fluidal or quasi-fluidal body, or is it essentially a crystalline body? No one questions that it is partly the one and partly the other, but which is it dominantly in its working habit? If the main mass of the interior is fluidal or quasi-fluidal, the whole may well be viscous or plastic in its body habit and yield indefinitely and continuously to stresses that tend to deform it. Continuous loading may, in this case, be followed by continuous subsidence; continuous unloading, by continuous uprising, if hydrostatic equilibrium had been disturbed. Not so with a typical crystalline mass. The crystalline structure has for one of its essential features the definite arrangement of the molecules of each crystal in determinate positions with reference to adjacent molecules. Any stress that tends to move them from these determinate positions is resisted by an elastic force· Up to the elastic limit a strain only results, not a shear. Deformation is thus specifically limited until the elastic yield-point is reached· Beyond this the mass may be sheared, granulated, or fractured.

When crystals are intimately interlocked, as they are in typical holocrystalline rocks, the joint mass partakes of the qualities of the interlocked integers. In such a firm interlocking of elastico-rigid units, stress gives rise to strain, but not to continuous shear, up to the yield-point of the elastic mass or of some of its integers. Beyond this—but in the main only beyond this—shear movement or fracture movement may take place. Stresses must thus accumulate to a certain value before appreciable movement will set in. In this lies a basis for periodic movement in distinction from continuous movement, for under growing stress there is practically no movement until the yield-point is reached, when distinct and relatively free movement follows until the stress is eased.

Notwithstanding the radical difference between the behavior of a plastic and of an elastic body respectively under constantly growing stress, there are two ways in which deformative movements in bodies of the elastic type may simulate in outward aspect those of the plastic type. In an elastic crystalline body, a more or less gradual movement may take place when the interlocking crystals are so constituted that the stresses brought to bear on the whole mass are concentrated upon certain points at which the crystals press with so much special intensity and inequality upon one another that the point of solution, fusion or fracture is reached for these minute parts under these exceptional and unequal stresses. These minute parts then yield, and the dissolved, fused or granulated material readjusts itself at neighboring points of less stress. This material may or may not resolidify. By this yielding, similar intensified stresses are thrown upon other points which yield in turn. Thus a succession of yieldings of minute points is brought into play while the main mass remains more or less massively solid. It is a combination of two modes of movement—liquid, plastic, or granular movement at minute points, and massive movement for the rest. There is crystalline loss and usually a crystalline gain by transfer. The action is thus usually motion and metamorphism combined. The action is partial and distributive, in detail, and the *tout ensemble* very closely simulates a plastic movement—which indeed it is in part, but not as a whole. It is commonly interpreted as plastic, though it is not simply such. The best type is glacial motion.[1] When the temperature of a glacier is 0° C. and it is thus on the very border of liquidity, and when it is bathed in water on the very border of solidity, as it is when melting is in progress, the change from ice to water and water to ice takes place with the utmost ease and is greatly facilitated by slight differences of stress. Glacial motion may then be almost as continuous and free from appreciable strains, ruptures and starts as the motion of a viscous body. But when the temperature is much lower and pervades the whole mass, its texture, and behavior are more rocklike, and strains, ruptures, starts, and microseismic phenomena are more pronounced. The mass is of course a crystalline rock of singular purity and the phenomena of strain, rupture, and start imminent in all cases under sufficient differential stresses. Crystalline orientation prevails at all stages.

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[1] "A Contribution to the Theory of Glacial Motion," *Decennial Publications of the University of Chicago*, 1904, pp. 193–204. See also Chamberlin and Salisbury, *Geology* I (1904), 294–306.

The second case is found when the pressure on all sides is so intense that no separation of particles is possible and hence *continuity of contact* is forced, whatever may be the nature of the deformation that arises from the *differential* portion of the pressure, *which alone can give a typical deformative movement.* Such a deformation may take on the *aspect* of plastic deformation even though the minute process be one of granulation, or of progressive recrystallization, or otherwise.

These modes of pseudo-plastic movement, or, at most, partially plastic movement, qualify the distinctness between deformative movements normal to viscous or plastic bodies, on the one hand, and to rigid elastic bodies, on the other, without destroying the radical differences in their fundamental natures. The similarities in external aspect are of course a source of difficulty in interpretation. It is none the less necessary to take account of the distinctiveness of the opposed qualities. The nature of viscous or plastic bodies is favorable to continuous deformative movements so long as unequal stresses continue to arise. The nature of elastico-rigid bodies requires the delay of deformative movements until the inequalities of stress have reached the elastic limit of the aggregate or of its most stressed points. This difference gives the key to the interpretation of terrestrial deformations. It is in this difference that the phenomena of base-leveling, shelf-building, and sea-transgression, of the types we have set forth, find their elucidation. They seem to imply a crystalline elastic-rigid constitution of the earth-body.

There are of course other methods of determining the nature of the earth-body, such as the modes of the seismic vibrations that traverse the earth, the time-relations of the body-tides to the passing of the tide-producing bodies, and so forth. The testimony of these is indispensable to a full consideration of the nature of the earth-body, but we are here considering merely the bearing of the strictly geological arguments that spring from gradational phenomena.

As previously urged, a base-level of wide prevalence is practically impossible if diastrophic movements are in continuous progress, for warping and dislocation are inherently inimical to mature planation. So too in shelf-building, the range within which wave action is effective in distributing sediments, and the depth within which light is effective in photo-synthesis, are so narrow compared with the ranges through which warping and dislocation shift the crust that relatively little diastrophism would forestall the formation of great parallel sets of strata and wide continuity of shallow-water life.

This will become clearer, and certain additional considerations will be brought into view, if we follow out systematically a normal evolution under each of the two types now basally distinguished.

The systematic evolution of a continent under continuous diastrophism is most easily followed if we accept the view that the mean specific gravity of the continental masses is lower than that of the suboceanic masses and that a certain tendency to isostatic equilibrium between the two arises from this difference of specific gravity—a view strongly supported by concurrent lines of evidence. Probably all will agree to this in some degree at least, whatever limitation or qualification they may wish to impose upon it. If this be accepted, it is not material to our immediate purpose whether the diastrophism is actuated by internal changes of volume, by the transfer of matter and energy from below to the surface, by the transfer of matter from higher to lower levels on the surface, or by all combined, or by other agencies, for the trend toward isostatic equilibrium permeates all and, to the extent of its value, gives shape to their effects in accordance with mechanical laws. The portions of the crust that are already bowed outward, and are at the same time lighter than the average, are inevitably bowed upward under further stress, and the portions that are already sagged, and are at the same time heavier than the average, are inevitably bowed downward, unless these actions are thwarted by exceptional intercurrent agencies. This inevitable tendency is made the more certain of realization by the constant unloading of the lighter outward-bowed portions and the constant loading of the heavier sagged portions. This must hold true whether the process of deformation be continuous or periodic.

Now, if the process be strictly continuous, as must be the case if a nearly perfect and constant isostatic equilibrium is maintained between the oceanic and continental segments, and between their larger parts among themselves, the evolution of the continents may be followed with logical ease. The continents must rise as they are unloaded and the ocean basins must sink as they are loaded. A secondary result must be a counter movement of the suboceanic material by virtue of which it pushes beneath the eroded continents to compensate their loss. The obviousness of this appears at once if perfect fluidity, the condition of perfect isostasy, is substituted for the existing rigidity that masks the real trend of present tendencies. A perfect adjustment would then take place promptly by vigorous movements of the kind indicated. If a viscous condition were substituted for that of free fluidity, the process would be slower but none the less inevitable. If the viscosity were high, the process would be greatly delayed but would follow the same lines. If the inequalities of specific gravity hold for the larger topographic features, the tendency will be to reproduce them, for the most protuberant portions are most eroded, in general, and suffer most from transportation. They are hence most lightened and must be most elevated in a strictly isostatic process. The continent is thus forced to reproduce itself automatically and, in theory, must continue to do so until the actuating agencies, the primitive differences in specific gravity, are removed.

This alternative cannot apparently be accepted, for the gradational phenomena seem to be decisively against it.

If we turn to the alternative view, and assume that the body of the earth is essentially crystalline, and is rigid up to the elastic limit of the most stressed points of the crystals, and that, aside from strain, the mass does not move until the elastic limit or the solution or fusion limit of the stressed points is reached, deformation naturally becomes fundamentally periodic. As already remarked by way of qualification, a multitude of minute local periodic motions may so combine as to give the semblance of a continuous motion, but even in this case the precise mode of action and the nature of the effects differ radically from continuous fluidal or plastic flow. Normally, in an elastico-rigid earth, strains should accumulate until they attain marked intensity and should then yield either to a slow massive movement of great magnitude—as is the common case in ordinary diastrophism—or else to a sudden swift movement of less magnitude—as is the case in earthquakes. The latter type is demonstrably non-continuous. There is certainly a period of accumulating strain, with inappreciable motion, followed by quick and often catastrophic movement. Between this class of demonstrative actions and the almost continuous phases of creep, there is believed to be a graded series of cases in each of which the movement is in essence periodic though the general expression varies from nearly continuous movement to sharply periodic movement. In the latter case there may be long intervening stages of relative quiescence.

Periodic movements of all these varieties are consistent with the acceptance of a qualified doctrine of isostasy, i.e., approximate isostasy attained by periodic movement, not complete isostasy attained by continuous movement. This qualified isostasy may be nearly complete, so far as vertical balancing is concerned, just after the periodic movement has ceased. Afterward there is a gradual departure from a strict balancing while stresses are reaccumulating. This leads on to a renewed movement of adjustment and so the periodic process continues. There is in this a rhythmical approach to isostasy.

Now this seems to meet the conditions of the case. It has already been repeatedly urged that the base-leveling process cannot normally reach the stage of an advanced peneplain if continuous warping of the crust is in progress. On the contrary, the crust must hold an approximately static attitude long enough for the gradational process to accomplish the results observed. It has been further urged that there goes with the base-leveling process an important class of marine deposits and a typical kind of life. So far then as the testimony of these highly important formations bear on the problem of continental rejuvenation, they imply that it was not a continuous steadily progressive process but that it recurred at such wide intervals as to permit great advances toward mature base-leveling as well as the evolution of shelf-seas, of parallel terranes, and of cosmopolitan faunas. All this seems in turn to imply an elastic, rigid, crystalline earth. The form of isostasy that is compatible with this has its working method in periodic approaches to complete isostasy through the successive accumulation and easement of strains in the body of the earth.